



Simulated adaptation strategies for spring wheat to climate change in a northern high latitude environment by DAYCENT model

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ABSTRACT

In order to identify strategies to support global food security while protecting the environment under future climate in northern high latitude environments such as the Canadian Prairies, the DAYCENT model was calibrated, validated, and subsequently used to project effects of climate change (increased carbon dioxide concentration, precipitation, and temperature), nitrogen (N) application rate, and yield potential (radiation use efficiency of biomass, RUE_B) of spring wheat (*Triticum aestivum* L.) on yield production and environmental outputs. Results indicated that projected grain yield and environmental impacts, i.e. soil organic carbon (SOC), N leached below root zone and nitrous oxide (N₂O) emission, are affected by different climate change scenarios, N fertilizer rate and RUE_B. From these results, we can assess impacts of fertilizer rates on projected grain yield and environmental impacts (SOC, N leaching and N₂O emission) in the near future (2017–2046) and distant future (2047–2076). In the near future, if wheat RUE_B is improved from current 38–43 mg C kJ^{−1}, the projected yield over seven climate change scenarios will increase 35% with a fertilizer rate of 100 kg N ha^{−1} compared to the current rate (50 kg N ha^{−1}). Corresponding increases of N leaching, N₂O emission and final SOC in 2046 are 29, 35 and 12%, respectively. Additional increases of yield and SOC will be small if more N is added, while N leaching and N₂O emission will be further increased. Assuming the cultivar grown in the distant future is improved to 53 mg C kJ^{−1} RUE_B and the fertilizer rate is raised to 125 kg N ha^{−1}, projected yield, N leaching, N₂O emission and final SOC in 2076 will be increased by 69, 26, 56 and 80%, respectively. If the N input is increased to 150 kg N ha^{−1}, corresponding increases will be 83, 30, 103 and 151%. It seems that appropriate N input could be 100–125 kg N ha^{−1} for the near future and distant future, respectively in order to balance production and environmental impacts. Results of our study indicated that after modification and calibration, DAYCENT model can be used to identify adaptation strategies for food security and environmental protection in high latitude environments under future climate change.

1. Introduction

Canada accounts for about 4% of global wheat (*Triticum aestivum* L.) production. Canadian total wheat production has averaged 30 million

tonnes between 2012 and 2016, grown across an area of 9.7 million hectares making it the largest field crop in Canada (Statistics Canada, 2016). Spring wheat and durum wheat (*T. turgidum* L. subsp. *durum* (Desf.) Husn.), account for about 95% of the seeded area and are grown

Abbreviations: CWRS, Canada Western Red Spring wheat; N₂O, nitrous oxide; RUE_B, radiation use efficiency of biomass; SOC, soil organic carbon; A2, A1B and B1, the third generation Canadian Global Climate Model with forcings based on the IPCC SRES greenhouse gases emission scenario A2 A1B and B1 respectively; C45 and C85, Canadian Centre for Climate Modelling and Analysis second-generation Earth System Model under concentration pathways RCP4.5 and RCP8.5 respectively; H45 and H85, Hadley Centre Global Environment Model version 2 under concentration pathways RCP4.5 and RCP8.5 respectively

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throughout the Canadian Prairies from latitude 49°N to 59°N (DePauw et al., 2011a, 2011b). About 70% of production is exported, making Canada among the world's largest exporter of wheat. The global demand for food and other agricultural products, such as feed, fibre and biofuels, is increasing due to population growth and changes in diets and life styles. Hence, agricultural production must increase tremendously for the next few decades (Alexandratos and Bruinsma, 2012). According to the report authored by the Food and Agriculture Organization of the United Nations (FAO, 2009), world food production will need to increase by 70% from 2005/2007 to 2050. Strengthening Canada's contribution to future global food security while protecting the environment at the same time is a significant challenge for Canadian producers.

Nitrogen (N) is an essential plant nutrient. Fertilizer N rate recommendations on the Canadian prairies generally consider factors such as soil texture, residual soil nitrate levels, soil moisture at seeding, average growing season precipitation, previous crop grown, crop to be grown, target grain yield, expected commodity prices and N fertilizer prices (Agriculture, 1988; Adler et al., 2007; Manitoba Agriculture, 2007). Hungate et al. (2003) indicated that projected increases in atmospheric CO₂ concentration in the future climate will cause a large nitrogen uptake by the crop and thus larger fertilizer applications may be required. Excessive nitrogen fertilizer application may result in negative environmental consequences, such as water contamination with nitrates and atmospheric emissions of nitrous oxide (N₂O), a potent greenhouse gas (Baggs et al., 2003; Iurii et al., 2014). Although greater rates of N fertilizer increased yield in some areas (Campbell et al., 2011), over-fertilization also occurred in some locales of the Canadian Prairies (Malhi et al., 2001). Therefore, fertilizer recommendations to optimize yield while minimizing environmental impacts is very site specific. Several studies have reported that emission of N₂O will likely increase in North America under climate change (Tian et al., 2012; Xu-Ri et al., 2012). Using the dynamic land ecosystem model Tian et al. (2012) projected that by the end of 21st century, N₂O emissions in North America would increase by 157–227% compared to emissions in the 2000–2010 period, assuming no change in management. Smith et al. (2013) indicated that N₂O emissions per tonne of wheat were projected to increase across most of western Canada by about 60% on average under the SRES A1 B and A2 scenarios and by about 30% under B1 scenario. The main reason for the reported projected increase in N₂O emissions compared to the baseline is increased N fertilizer use (Denman et al., 2007), but other factors such as soil moisture and temperature, occurrence of freezing and thawing events, soil type, land use, and management affect the emission rate (Dusenbury et al., 2008; Bouwman et al., 2010).

Soil nitrate leaching on the Canadian prairies is generally thought to be minimal because potential evapotranspiration exceeds precipitation by a wide margin (Reynolds et al., 1995; Fairchild et al., 2000; De Jong et al., 2009; Janzen et al., 2003). From 1967–2005 the annual potential evapotranspiration (510 mm) was 43% higher than annual precipitation (356 mm) at Swift Current, Saskatchewan (Kröbel et al., 2012). Yet, nitrate (NO₃⁻-N) leaching beyond the root zone of annual crops in the prairie provinces of western Canada has been observed, especially in fallow soils (Campbell et al., 2010). Over fertilization may increase the risk of NO₃⁻-N leaching (Campbell et al., 2006a, 2006b; Lemke et al., 2012a). Under fertilization could also cause leaching because of low plant utilization of available N (Lemke et al., 2012a). Continuously cropped treatments showed little evidence of leaching loss (Lemke et al., 2012a, 2012b). Much of the modeling work on N leaching under the impact of climate change projected increased leaching in the future mainly caused by projected increases in precipitation and N fertilizer application (Eckersten et al., 2001; Olesen et al., 2007; Ulén and Johansson, 2009; Qian et al., 2010; Jaradat and Boody, 2014; Forsius et al., 2013). However, De Jong et al. (2008), projected that with no changes in agricultural practices, N leaching under future climate change (2040–2069) in Prince Edward Island, Canada would remain

very similar to that simulated under historic climatic conditions. With agricultural intensification, in response to climate change and economic conditions, estimates of soil N leaching increased by 5–30% beyond historic levels (De Jong et al., 2008).

The sustainability of wheat production on the Canadian prairies has been maintained by the adoption of conservation tillage and management. These changes resulted from soil conservation practices, especially no-till, which can reduce soil erosion (Cutforth and McConkey, 1997), improve soil quality (Campbell et al., 1989), and increase soil carbon (C) sequestration (Campbell et al., 1996, 2000, 2001) compared with conventional practices (i.e. summer fallow and frequent tillage). It is not conclusive, however, regarding the effect of climate change on soil organic carbon (SOC) on the Canadian Prairies. Smith et al. (2009a) projected that crop yields could increase in eastern Canada, while SOC will be reduced due to greater rates of decomposition. Similar results were obtained by Smith et al. (2009b) and Pan et al. (2013). Morgan et al. (2011) reported that climate change may increase SOC in semiarid grasslands of the western Great Plains of North America. Recently, Smith et al. (2013) indicated that soil carbon should remain relatively stable in the future with small amounts of C sequestration occurring when biomass production and C inputs increase substantially.

Under the projected climate change scenarios (CGCM2 A2, CGCM2 B2, HadCM3 A2, and HadCM3 B2) increased temperature, and water stress could decrease crop yield in many regions of the world. But research results are not consistent on the Canadian Prairies, a northern high latitude area. Qian et al. (2013) indicated that climate change may benefit agricultural production in Canada. Rosenzweig et al. (1999) projected that a 2 °C increase in temperature with no precipitation change could result in wheat yield increases when the direct effect of CO₂ is taken into account in Canada. However, Deryng et al. (2014) projected a decrease in wheat yield in Canada because of the projected heat stress under climate change.

Many studies have been conducted on the impacts of climate change on crop yield and how to develop cultivars to cope with the changing climate. However, few studies considered the effects of cultivars with different yield potential (RUE_B, radiation use efficiency of biomass, represented by the parameter of [PRDX(1)], which is a coefficient for calculating potential aboveground production as a function of solar radiation outside the atmosphere, mg C kJ⁻¹). Yield gains have been difficult to achieve for Canadian hard red spring wheat because of the stringent quality requirements and environmental constraints of a short growing-season, limited rainfall, and high growing season temperatures (Wang et al., 2012). Over the 90 years between 1902 and 1992 the yield potential of Canada Western Red Spring wheat (CWRS) increased at a rate of 0.23% yr (McCaig and DePauw, 1995). Beginning in 1991, it rose by the rate of 0.7% yr (Thomas and Graf, 2014) due to increased investment in genetic enhancement and application of new breeding technologies. Smith et al. (2013) assumed new cultivars might require increased growing degree days. In general, because of the short growing season and stringent requirements for wheat market classification, and environmental constraints in western Canada, genetic improvements in yield in the past decades were not associated with the increase in growing degree day requirement for maturity. Rather increases in grain yield were associated with kernel number, size, grain filling rate as well as carbohydrate and N remobilization (Wang et al., 2002, 2003). However, over the past 27 years the time to maturity of new cultivars has increased by several days. When cultivar Katepwa (Campbell and Czarnecki, 1987), released in 1981, and cultivar Carberry (DePauw et al., 2011a, 2011b), released in 2009, were grown together in more than 30 replicated trials over three years, Carberry required 3.5 days more to mature while yielding 14% more grain and 2% more protein concentration. Because some areas of Europe are experiencing hotter and drier summers, Semenov et al. (2014) indicated a quicker maturation of wheat cultivars helped them to escape excessive heat and drought stress. Future climate is projected to have an increase in frequency of heat stress at meiosis and anthesis for wheat; therefore,

Semenov et al. (2014) suggested that increased tolerance to heat and drought stress should remain priorities for the genetic improvement of wheat.

A cropping system is complex in terms of interactions of the plants with the soil physical, chemical and biological characteristics under the changing environment, characterized as “Genotype x Management x Environment”. To address all the issues discussed above and to find a suitable strategy to increase yield while protecting the environment under future climate, a process-based modeling approach is desirable (Carter et al., 2011). As a result, we selected the crop model DAYCENT (Parton et al., 1994) for this study because (1) DAYCENT is an open source, process based model, which allows scientists around the world to examine, verify, test the validity, adequacy of the model, and to collaborate to improve and expand the model, and (2) DAYCENT has been used for various applications in North America (Del Grosso et al., 2005, 2008).

The objective of this study was to use the DAYCENT model to project climate change impacts, in a northern high latitude, on wheat yield, the environment, and to identify future strategies to increase wheat yield while safeguarding the environment on the Canadian Prairies. In this paper, we selected a study site to (1) calibrate and test the DAYCENT model, (2) use the model to project yield and environmental consequences under the effects of seven future climate change scenarios, seven N fertilizer application rates, and cultivars with four different yield potentials and their interactions, and (3) to identify the best management practices.

2. Materials and methods

2.1. The DAYCENT model

DAYCENT, the daily time-step version of the CENTURY biogeochemical model (Parton et al., 1994), was selected for this study. DAYCENT is a widely used process-based ecosystem model. This model has been tested with data from various native and managed systems (Del Grosso et al., 2001a, 2002, 2005). It has been used extensively to simulate grassland and crop yields (Del Grosso et al., 2002, 2005, 2008; Hartman et al., 2011). The model has been used to evaluate the environmental impacts of growing crops (Adler et al., 2007; Davis et al., 2010). Comparison of mean annual soil N₂O flux estimated by DAYCENT and IPCC emission factor (EF) (IPCC, 2006) with measured multi-year and multi-location data for different cropping systems in North America yielded R² values of 0.74 and 0.67, and mean deviations of −6% and +13%, respectively (Del Grosso et al., 2005). The United States Environmental Protection Agency, United States Department of Agriculture and the Colorado State University Natural Resource Ecology Lab used DAYCENT to develop a national inventory of N₂O emissions from U.S. agricultural soils. This inventory was compared and contrasted with the existing Intergovernmental Panel on Climate Change (IPCC) agricultural N₂O emissions inventory for the United States (Del Grosso et al., 2006). Results showed that DAYCENT generated more reliable results because it accounted for factors such as soil type, climate, and tillage intensity that are ignored by some other methods (Del Grosso et al., 2005). This demonstrated the strengthened ability of the DAYCENT model when using both point and large-scale simulation applications.

Key sub-models of DAYCENT include soil water content and temperature by layer, plant production and allocation, decomposition of litter and soil organic matter, mineralization of nutrients, N gas emissions from nitrification and denitrification, and methane oxidation in non-saturated soils. Flows of C and N between the different soil organic matter pools are controlled by the size of the pools, C/N ratio and lignin content of material, and abiotic water/temperature factors. Plant production is a function of genetic potential, phenology, nutrient availability, water/temperature stress, atmospheric CO₂ concentration and solar radiation. Net primary production is allocated to plant

components (e.g., roots vs. shoots) based on vegetation type, phenology, and water/nutrient stress. Nutrient concentrations of plant components vary within specified limits, depending on vegetation type and nutrient availability relative to plant demand. Decomposition of litter and SOC and nutrient mineralization are functions of substrate availability and quality (lignin% and C/N ratio), and water/temperature stress. Fluxes of N gas from nitrification and denitrification are driven by soil NH₄⁺-N and NO₃[−]-N concentrations, water content, temperature, texture, and labile C availability. DAYCENT simulates fluxes of C and N among the atmosphere, vegetation, and soil (Del Grosso et al., 2001b).

The accuracy with which a model represents the natural system observed in the field depends on how completely the underlying biophysical processes are represented in the model and how well the model parameters are calibrated to field observations. As an open source model, information about DAYCENT can be downloaded through the website (<http://www.nrel.colostate.edu/projects/daycent-downloads.html>), and the current version of DAYCENT and/or source code is also available by communication through the email: century@colostate.edu.

2.2. Model modification, calibration and validation

Slight modifications were made to DAYCENT V4.5 to facilitate our simulation purpose. First, in consultation with the developer, the code was changed to enable the model to simulate soil to the depth of 10 m. The original depth was 4 m, which might not have been deep enough to project soil nitrate dynamics and leaching (Agriculture, 1988). Secondly, we simulated the effect of atmospheric CO₂ concentration on plant growth from the start of the simulations. We did not use the step function or ramp function provided by DAYCENT to calculate the change of CO₂ concentration over the years; instead we use measured historical data (Keeling et al., 1976; Thoning et al., 1989; Etheridge et al., 1998) and projected yearly concentration under different climate change scenarios provided by IPCC (IPCC, 2000) and RCP4.5 and RCP8.5 concentration pathways (Meinshausen et al., 2011). The baseline CO₂ concentration was set to 400 ppm and projected CO₂ concentrations were 661, 711, 550, 531 and 758 ppm for A1B, A2, B1, RCP4.5 and RCP 8.5, respectively in 2076.

2.2.1. Model calibration

Measured soil organic carbon content from the rainfed Tillage Study was used for model calibration. This study was conducted near Swift Current Research and Development Centre (SCRDC), Agriculture and Agri-Food Canada, Swift Current, Saskatchewan, Canada on an Orthic Brown Chernozem soil with a silt-loam texture. The annual average temperature and total precipitation are 5.1 °C and 351 mm (1961–2010), respectively. The first cultivation started about 1900 and had fallow–wheat rotation using conventional tillage methods until the initiation of the study in 1982. More site information is indicated in Table S1. Treatments in the Tillage Study were arranged in a randomized complete block design (RCBD) with four replications. Details of the Tillage Study have been given by McConkey et al. (1996).

A 5000 year DAYCENT spin-up run was conducted for the Tillage Study soil to let the SOC and its pools reach an equilibrium state with a total of 66.5 t ha^{−1} SOC at the depth of 0–30 cm, which was based on an assumption that about 35% of the original SOC had been lost by 1982, when measured SOC was 43 t ha^{−1} (Monreal et al., 1997).

Because SOC is sequestered via plant growth, we adjusted RUE_B to let the simulation reach expected SOC. We used the growth parameters for a “50% cool season and 50% warm season mixed grass with some legume N fixation” grassland from the DAYCENT crop.100 file to simulate the growth of pre-cultivation grassland. The RUE_B was adjusted to 10 mg C kJ^{−1} to let the simulation reach an equilibrium state at 66.5 t ha^{−1}. The model then simulated land breaking in 1910 (Curtin et al., 2000) followed by a fallow–wheat rotation from 1910 until the

initiation of the Tillage Study in 1981. The RUE_B for the older spring bread wheat cultivars grown between 1910–1981 was adjusted to 33 mg C kJ^{-1} to allow simulated SOC to match measured SOC values in 1982 (43 t ha^{-1}). The minimum and maximum aboveground biomass C/N ratios with the maximum biomass were adjusted to 28 and 100, respectively, to maintain grain N concentration, an important quality parameter for bread wheat, to be $> 2.5\%$ at maturity when soil available N is not deficient (Campbell et al., 1997). From 1981, the initiation year of the Tillage Study, the model simulated the continuous wheat no-till cropping system. The RUE_B for the newer spring wheat cultivars grown for this study was adjusted to 38 mg C kJ^{-1} to allow simulated SOC fit the observed SOC values measured in the later years.

2.2.2. Model validation

Other observation data from the Tillage Study and data from four other studies (Conventional Farming Study, Conservation Farming Study, Fertilizer Study and Physiology Study) conducted in the same site under rainfed conditions were used for model validation.

2.2.3. Tillage study

Model validation data are: 1) aboveground biomass, grain yield, soil moisture, and nitrate concentration in the continuous wheat no-till treatment, and 2) aboveground biomass, grain yield, soil moisture, nitrate concentration, and SOC in the continuous wheat conventional tillage treatment. The conventional tillage management treatment was basically the same as the no-till except that the soil was tilled once a year, prior to seeding, using a heavy-duty sweep cultivator with an attached dead rod or mounted harrow.

2.2.4. Conventional farming study

This study was initiated in 1966 at SCRDC, AAFC. The overall objectives were to evaluate the influence of rotation length, fallow substitute crops, and fertilizers on crop yields, environment, and economic returns. All rotations were replicated three times within a RCBD. Each plot is 10.5 m by 40 m . Detailed descriptions of the study were given by Campbell et al. (2005) and Lemke et al. (2012a). Plots to be planted generally received one pre-seeding tillage operation with a heavy-duty sweep cultivator and mounted harrow. On average, fallow plots received about four tillage operations (mainly cultivator and rodweeder). Aboveground biomass, grain yield, soil moisture, root-zone nitrate concentration, and SOC were measured every year. While the variable, NO_3^- -N leached below the root-zone, was only measured in the fall of 2003 and spring of 2004 in the continuous wheat treatments of the high N and low N fertilizer rate applications (Zentner et al., 2003). For the high N treatment, fertilizer N rates were determined based on amounts of soil nitrate ($0\text{--}60 \text{ cm}$ soil layer) measured in individual plots from soil samples taken in the previous fall to bring total mineral N (soil N + fertilizer N) to 65 kg N ha^{-1} from 1967 to 1990 and to 73 kg N ha^{-1} from 1991 to 2015. For the low N treatment, no N was applied except for that in P fertilizer monoammonium phosphate. On average, total N inputs were 40 and 7 kg N ha^{-1} for the high N and low N treatment, respectively. The rate of monoammonium phosphate was 10 kg ha^{-1} for both treatments each year. The DAYCENT model was run for each replication with different N inputs for the high N treatment.

2.2.5. Conservation farming study

Initiated in 1987 at SCRDC, the Conservation Farming Study was designed to evaluate, under conservation tillage management, the influence of crop and rotation type on crop productivity, environment, and economic performance. Plots were $15 \text{ m} \times 45 \text{ m}$, arranged in a RCBD with three replicates. The plots were tilled only when necessary for proper weed control or seed placement. Details of this experiment have been reported by Zentner et al. (2003) and Lemke et al. (2012b). The variables above-ground biomass, grain yield, soil moisture, root-zone nitrate concentration, SOC, and nitrate leaching measured in the

fall of 2003 in the continuous wheat treatment (Campbell et al., 2006a, 2006b) were used for model validation. The DAYCENT model was run for each replication with different N inputs.

2.2.6. Fertilizer study

The Fertilizer Study was conducted at SCRDC from 2000 to 2002 to determine the effect of N fertilizer form (urea and anhydrous ammonia), placement (broadcast, side-band or mid-row band), timing (fall or spring), and rate ($0, 30, 60$ and 90 kg N ha^{-1}) under no-till on yield performance and N_2O emission. Each N rate should add 90 kg N ha^{-1} from the P fertilizer (monoammonium phosphate) at rates of 7 kg P ha^{-1} . Plots were arranged in RCBD with four replicates and were $3.1 \times 9.2 \text{ m}$ in size. Grain yield, biomass and N_2O emission from spring wheat treatments fertilized in the spring were used for model validation. Fluxes of N_2O emission were estimated from the concentration change in the chamber headspace over a 30 or 60 min collection period. Samples were drawn from the headspace using disposable 20 ml polypropylene syringes. The gas samples were then injected into pre-evacuated 13 ml exetainers for transport to the laboratory. The concentration of N_2O in the samples was determined using a gas chromatograph equipped with an electron capture detector. The field plots were sampled for N_2O emissions about twice weekly from snow melt until the end of July when soil-water contents were high. Sampling frequency was reduced to once a week or less during the latter part of the season when soil-water content was low. Annual estimates of N_2O emissions were calculated by interpolating between data points and integrating over time assuming a constant flux. Details of this study have been provided by Lemke et al. (2009) and Mooleki et al. (2010).

2.2.7. Physiology study

The Physiology Study was conducted at SCRDC from 1998 to 2001 to determine the physiological basis of current high-yielding and high-quality bread wheat cultivars grown on the Canadian Prairies (Wang et al., 2002, 2003). The field design was a RCBD with four replicates with $3 \times 3.7 \text{ m}$ plot size. Based on soil tests (top 30 cm) from the previous October for each year, monoammonium phosphate and ammonium sulphate were broadcast before seeding to bring total mineral N and P to 112 kg ha^{-1} and 67 kg ha^{-1} , respectively. Detailed descriptions of the study have been provided by Wang et al. (2003). Measurements of grain yield, grain N concentration, straw yield and N concentration were used for model validation.

2.3. Development of future climate scenarios

Arbitrary meteorological factors (daily maximum and minimum temperature, and precipitation) were generated by a stochastic weather generator developed at Agriculture and Agri-Food Canada (AAFC-WG), based on climate change simulated by a Canadian Global Climate Model (CGCM3) with forcing based on the IPCC SRES greenhouse gases emission scenarios A1B, A2 and B1. Two representative concentration pathways RCP4.5 and RCP8.5 for climate scenarios based on the Canadian Centre for Climate Modelling and Analysis second-generation Earth System Model (CanESM2, C45 and C85) and the Hadley Centre Global Environment Model version 2 (HadGEM2, H45 and H85) were also used in this study. Detailed information for the development of future climate scenarios is provided in the Supplementary Information.

2.4. Effects of N fertilizer and wheat yield potential under climate change

The simulation continued on from the current scenario to the period of 2017 – 2076 under climate change scenarios A1B, A2, B1, C45, C85, H45, H85 and the baseline synthetic weather data for the no-till continuous wheat on the Tillage Study. For N fertilizer rates, we used the current application rate (50 kg N ha^{-1} , the average rate from 1981 to 2014 was 52 (standard error ± 12) kg N ha^{-1}), reduced rates with zero and half (25 kg N ha^{-1}) and increased rates of 1.5 (75 kg N ha^{-1}), 2.0

(100 kg N ha⁻¹), 2.5 (125 kg N ha⁻¹) and 3.0 (150 kg N ha⁻¹) fold of the current rate. For the CWRS wheat, we used four levels of RUE_B: the current level at 38 and improved levels at 43, 48 and 53 mg C kJ⁻¹, which were increases of 13, 25 and 38%, respectively. Grain yield could be increased in many ways, such as increasing harvest index, improving morphology to receive more solar radiation, increasing root uptake of nutrients, and improving photosynthetic capacity as recommended by recent studies (Murchie et al., 2009; Reynolds et al., 2009; Sun et al., 2009). Fischer et al. (1998) observed that the maximum photosynthetic rate of wheat cultivars released from 1962 to 1998 increased 23%. Chytky et al. (2011) found that a CWRS wheat cultivar, McKenzie had 25 and 41% higher light saturated light and CO₂ saturated maximal photosynthetic rates than another hard white spring cultivar, Snowbird, respectively. DAYCENT-projected wheat grain yield, aboveground biomass, SOC at 30 cm, soil nitrate N at root zone (0–1.2 m, Cutforth et al. (2013) and below root zone leaching (1.2–10 m), and greenhouse gas emissions were outputs used for analyses in this paper.

2.5. Statistical analyses and model test

Mean, lower and upper limits of the 95% confidence interval and standard deviations of the mean for measured values, while synthetic air temperature and precipitation under baseline and climate change scenarios were calculated values.

The goodness of fit of simulations with observations was performed by the lack of fit test (LOFIT, Whitmore, 2006). If the F value for the lack of fit is higher than the F critical values at the 0.05 probability level it indicates the error in the simulated values was significantly greater than the error inherent in the measured values. The lack of fit tests systemic errors, which allows the experimental errors to be distinguished from the failure of the model (Wang et al., 2012). This method uses replicated measurements to compare with simulations in a temporal series rather than comparing a single measurement against a simulated value.

The root mean square error of model (RMSE) was used to summarize the total differences between observed and predicted values. The significance of RMSE was assessed by comparing to the value obtained assuming a deviation corresponding to the 95% confidence interval of the measurements (Smith and Smith, 2007). The RMSE gives a relatively high weight to large errors.

The bias in the total difference between simulations and measurements was determined by calculating the relative error (RE) which was tested for significance with the method of Addiscott and Whitmore (1987). It assesses consistent or inconsistent errors in the simulations with respect to the observations. The significance of RE was determined by comparing to the value obtained assuming a deviation corresponding to the 95% confidence interval of the measurements. The Pearson's correlation coefficient (*r*) (Draper and Smith, 1996) was used to evaluate the association between simulated and measured values (precision). If the *r* value is significantly high, it may indicate that the structure of the model is appropriate.

Effects of climate scenarios, N fertilizer rates, yield potentials, and their interactions on DAYCENT-simulated outputs were analysed by combined analyses with SAS PROC GLM (SAS, 2009). The relative effect of each factor on an output factor was calculated with its sum of squares as a percentage of total sum of squares in the combined models.

3. Results and discussion

3.1. Model calibration

Heterogeneity of SOC under the no-till continuous wheat treatment of the Tillage Study changed with much lower heterogeneity for the period 1980–1996 compared to the period of 2000–2012 (Fig. 1). There was a significant increase in SOC 20 years after the introduction of continuous wheat no-till cropping. The calibrated model was able to

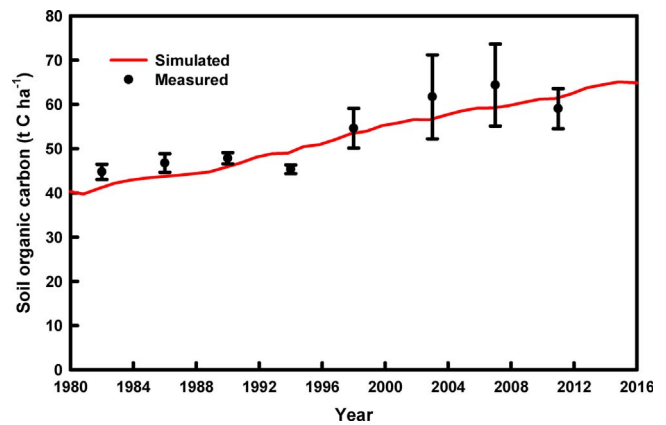


Fig. 1. Model calibration for soil organic carbon. The data were obtained from the continuous wheat cropping treatment under no-till in the Tillage Study at Swift Current Research and Development Centre, Agriculture and Agri-Food Canada, Swift Current, in southwest Saskatchewan, Canada. Vertical bars are standard deviations of observation mean.

project the changing trend of SOC and satisfactorily estimated values with very low *F*(LOFIT) and RMSE ($P < 0.05$), high *r* ($P < 0.001$), and low RE ($P < 0.05$) (Table S2).

3.2. Model validation

3.2.1. Continuous wheat treatments of the tillage study

Observations of grain yield and N concentration, above-ground biomass, soil nitrate concentration, and soil moisture in the root zone of spring wheat at 0–1.2 m of the continuous wheat no-till treatment of the Tillage Study were used for the model validation. All simulated variables were not significantly different from measured values by LOFIT test (F (LOFIT) $< F_{0.05}$) indicating that there was no evidence to suggest that the modeled and observed data were statistically different (Table S2). Relative errors were also significantly low ($P < 0.05$), except for soil moisture at 0–15 cm, confirming that the overall accuracies of the model assessments were reasonably high. Values of RMSE for SOC, soil nitrate and soil moisture at depths of > 30 cm are within the 95% confidence interval of the measured data, but not for biomass, yield, grain N or near surface soil moisture.

Over all validations, DAYCENT tended to overestimate grain yield and biomass, due to the fact that the model does not account for losses due to shedding of leaves, lodging, grain shattering, weeds, disease or insects (Rosenzweig et al., 1999; Quiring and Legates 2008; Wang et al., 2010). The model tended to underestimate the near-surface soil moisture (RE = 34.4%). Pearson's correlation between a simulated and measured variable was significant ($P < 0.001$) for all variables tested, except for grain N concentration (Table S2). This indicates that the structure of the DAYCENT model is generally sound for modeling wheat growth, SOC, soil nitrate, and moisture at 0–120 cm. The simulation quality for the continuous wheat conventional tillage treatment of Tillage Study was similar to the no-till treatment (Table S2).

3.2.2. Continuous wheat treatments of the conventional farming study

The model projected SOC, grain yield, grain N concentration, above-ground biomass, root zone soil nitrate concentration, and moisture satisfactorily for both high N and low N treatments under continuous wheat cropping on the Conventional Farming Study according to the tests of *F* (LOFIT), RMSE, RE, and *r*, except that *r* was low for SOC and soil nitrate concentration at 90–120 cm (Table S3) and the RMSE values for near-surface soil moisture are outside of the 95% confidence interval of the measured data.

The model simulated an increase in soil N leaching (nitrate concentration below the root zone, 1.2 – 4.5 m) in the conventional tillage of the fallow-wheat rotation. It was reduced after the adoption of

continuous cropping (data not shown). Although this trend can not be validated as deep soil sampling was only done once over the years. It was observed 37 years after the initiation of this study that fallow-containing rotations had higher leaching than non-fallow rotations (Campbell et al., 2006a, 2006b). The high N treatment had higher nitrate concentration than the low N treatment in most of the below root zone depths (Table S4). The DAYCENT-simulated nitrate concentration was within the 95% confidence intervals or close to the upper limit for most of the depths for both treatments, but the model tended to overestimate leaching in the depths of 2–3 m. The simulated means of all depths were slightly higher than the upper limit. The model-simulated difference between the two treatments was consistent with the observed data.

3.2.3. Continuous wheat treatments of the conservation farming study

Table S5 showed that DAYCENT was able to project SOC, grain yield, grain N, aboveground biomass, root zone soil nitrate concentration, and moisture of the continuous wheat cropping system on the Conservation Farming Study. However, the simulated grain N and root zone soil moisture were not correlated with measured values indicating that simulated results did not match the pattern of the measured values. The DAYCENT model tended to overestimate below root zone soil nitrate leaching at 1.2 – 2.1 m, but the projected average value from 1.2 to 2.4 m was only slightly higher than the upper limit of the 95% confidence interval for the measured mean (Table S6).

3.2.4. Fertilizer study

Although the DAYCENT model did not project N_2O emission very accurately, the majority of the confidence interval bars touched or were close to the 1:1 line showing near-satisfactory agreement (Table S7). The model also projected wheat biomass and grain yield quite well.

3.2.5. Physiology study

The model projected grain and straw yield and their N concentration reasonably well according to the tests of F (LOFIT) and RE, but the associations between simulated and measured values were not significant. Tests of RMSE tests indicated satisfactory estimations for straw yield and straw N, but not for grain yield or grain N (Table S8).

3.3. Projected change in yield under different climate scenarios, fertilizer and cultivar potentials

DAYCENT-projected yearly change of grain yields under different climate scenarios compared to baseline (%) with the N fertilizer rate of 100 kg N ha^{-1} and RUE_B 43 mg C kJ^{-1} (Fig. 2). Although there are high

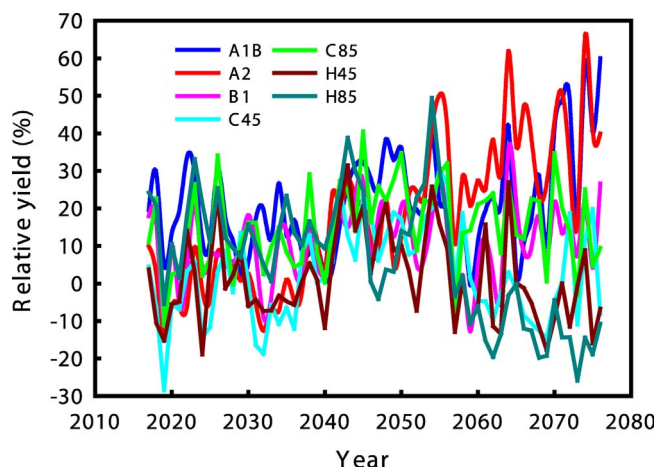


Fig. 2. DAYCENT-projected yearly grain yields from 2017 to 2076 under different climate scenarios A1B, A2, B1, C45, C85, H45 and H85 with the N fertilizer rate of 100 kg N ha^{-1} and RUE_B 43 mg C kJ^{-1} .

yearly fluctuations in DAYCENT-projected yield, we still found differences among climate change scenarios. Under scenario A1B, projected yield was significantly higher than that under the baseline climate in most years. From 2070 onward, the projected yields under A1 B increased linearly, which is related to the increase in projected precipitation (Fig. S1) and CO_2 concentration as well as a slowdown in temperature increase (Fig. S2). The projected yield increases compared to the baseline were 17% for the first 30 years and 26% for the second 30 years.

Under the A2 scenario, the mean projected yield in the first 30 years was only 4% higher than that under the baseline. In the second 30 years, the projected yield under A2 increased and was significantly higher than that under the baseline with 32%, which was associated with the projected increased precipitation and CO_2 concentration. The model projected the third highest increase of yield under C85 which was contributed by its high precipitation and CO_2 concentration. It's projected high air temperature, however, had a negative effect on the projected yield with increased water stress caused by high evapotranspiration and reduced photosynthesis caused by high temperature. The averaged increases of projected yield were 13 and 18% for the first and the second 30 years, respectively. The change of projected yield was small for the other four scenarios, with mean relative yields of 11%, 3%, 1% and 7% for B1, C45, H45 and H85, respectively, compared to the baseline. It was caused by less projected precipitation, high temperature in the case of C45, H45 and H85, and low CO_2 concentration in the case of B1, C45 and H45. To compare projected relative yields between the first and the second 30 years, A2 had the most increase (from 4 to 32%), followed by A1 B (from 17 to 26%). H85 had the most reduction (from 15 to -2%) and the change was small for the other scenarios. Averaged over all the fertilizer and cultivar treatments, the projected yields under climate change scenarios A1B, A2, B1, C45, C85, H45 and H85 were 31, 26, 12, 4, 20, 0 and 5% higher than under the baseline, respectively.

The increase in projected yield was near linear with the increase of N application from none to 100 kg N ha^{-1} under all climate scenarios (Fig. 3), then the rate of projected increase of yield was reduced. On average, increases of projected yield with an increase of each 25 kg N ha^{-1} fertilizer were 58, 33, 22, 16, 9 and 5% for rates of 25, 50, 75, 100, 125 and 150 kg N ha^{-1} , respectively. The responses of projected yield to N fertilizer differed among climate scenarios. The best was A1 and the worst was H85. For A2, increases of projected yield with an increase of each 25 kg N ha^{-1} fertilizer were 61, 34, 23, 17, 11 and 8% for rates of 25, 50, 75, 100, 125 and 150 kg N ha^{-1} , respectively (Fig. 3c). The corresponding increases were 55, 33, 22, 14, 7 and 3% for H85 (Fig. 3h). In terms of N fertilizer use efficiency, the averaged efficiencies over all climate scenarios were 38, 26, 21, 18, 16 and $14 \text{ kg grain C kg N}^{-1}$ for rates of 25, 50, 75, 100, 125 and 150 kg N ha^{-1} , respectively. The corresponding values were 45, 29, 24, 21, 18 and $17 \text{ kg grain C kg N}^{-1}$ for A1 B which had the highest N use efficiency and 34, 23, 19, 16, 14 and $12 \text{ kg grain C kg N}^{-1}$ for H45 which had the lowest N use efficiency.

According to the simulation, the improvement of RUE_B will increase yield (Fig. 3). The overall projected yield increases are 4, 7 and 9% with 43, 48 and $53 \text{ mg C kJ}^{-1} RUE_B$, respectively, compared with $38 \text{ mg C kJ}^{-1} RUE_B$ when the fertilizer rate is 100 kg N ha^{-1} . Under the baseline scenario the corresponding increases are only 3, 5 and 6%, respectively. Projected yield with the increase of RUE_B improved grain yield under all climate change scenarios compared to that under the baseline. The highest increase in projected yield was under H85 with increases of 7, 11 and 14% for 43, 48 and $53 \text{ mg C kJ}^{-1} RUE_B$, respectively, compared to the current cultivar with $38 \text{ mg C kJ}^{-1} RUE_B$.

This indicates the importance of genetic improvement to meet future climate change, which is in agreement with Slafer et al. (1999) and Araus et al. (2002). The change of projected yield affected by the change of RUE_B was relatively small compared to that affected by climate change scenarios and by the change of N fertilizer rate. Necpálková

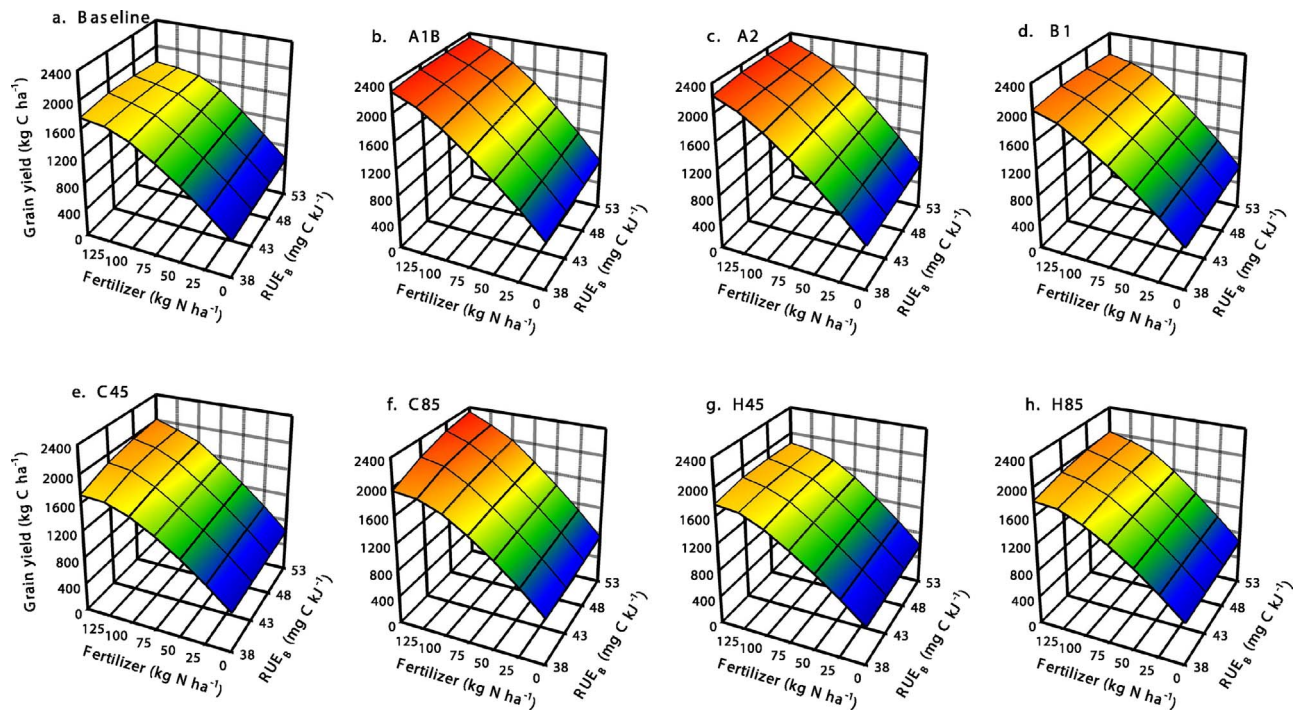


Fig. 3. Projected mean grain yield over 60 years (2017–2076) under different climate scenarios, N fertilizer rates and RUE_B .

et al. (2015) pointed out the sensitivity parameters determining RUE_B on wheat was very small. In addition to the increase of RUE_B , wheat yield potential could be improved by changing its morphological and phenological characteristics (Xue et al., 2008), which could be considered in future modeling work.

3.4. Projected change in aboveground biomass under different climate scenarios, fertilizer and cultivar treatments

The change in projected aboveground biomass over the 60 years of climate change compared to projections based on baseline scenario followed the same pattern of simulated grain yield (data not shown). Overall, contributions of climate scenarios, N fertilizer rate, and yield potential to the projected biomass, as well as the increase in biomass caused by yield potentials relative to the current cultivar are the same as found for projected yield. Compared to the baseline climate, the projected biomass is increased by 31, 26, 12, 4, 20, 0 and 5% for climate change scenarios A1B, A2, B1, C45, C85, H45 and H85, respectively (Fig. 4).

Mean N fertilizer use efficiencies over all climate scenarios were 101, 67, 54, 47, 41 and 36 kg biomass C kg N⁻¹ for rates of 25, 50, 75, 100, 125 and 150 kg N ha⁻¹, respectively. The corresponding values were 113, 75, 61, 53, 47 and 42 kg biomass C kg N⁻¹ under A1 B which had the highest N use efficiency and 95, 63, 51, 44, 37 and 32 kg biomass C kg N⁻¹ for H45 which had the lowest N use efficiency. Effects of improved RUE_B on projected biomass production were similar to that for projected grain yield.

3.5. Projected change in SOC under different climate scenarios, fertilizer and cultivar treatments

The model simulation showed that yearly changes in SOC were slow and gradual under the effects of climate change, N fertilizer rate, and wheat yield potential (data not shown). According to the simulation, if the N fertilizer is reduced from the current level (50 N kg ha⁻¹) SOC will be tremendously reduced at the end of the 60 years' simulation in 2076 compared to the current value (60 t C ha⁻¹) (Fig. 5). If the N rate is not changed, SOC will still be reduced by 3–9 t C ha⁻¹, no matter

which climate scenario or with what RUE_B , except when RUE_B was increased to 53 mg C kJ⁻¹ below baseline, A2 and H45, for which projected SOC was not changed. The worst scenario for losing soil carbon was H85 under which with no improvement of RUE_B (38 mg C kJ⁻¹), SOC will be reduced even if N fertilizer was increased to 150 N kg ha⁻¹. On average over all scenarios and RUE_B , projected changes of SOC were -19, -10, -3, 2, 6, 10, and 12 t C ha⁻¹ with N rates of 0, 25, 50, 75, 100, 125 and 150 N kg ha⁻¹, respectively. With the rate of 100 N kg ha⁻¹, the averaged changes of SOC were 9, 7, 10, 7, 3, 1, 9 and 6 t C ha⁻¹ below baseline, A1B, A2, B1, C45, C85, H45 and H85, respectively. With the rate of 100 N kg ha⁻¹, the averaged changes of SOC were 3, 5, 8 and 10 t C ha⁻¹ with 38, 43, 48 and 53 mg C kJ⁻¹ RUE_B , respectively. Our results are similar to the report of Smith et al. (2007) who reported that climate change is not the only reason to cause changes in SOC. In DAYCENT, SOC was much more sensitive to parameters describing the decomposition rates than to the parameters driving carbon inputs (Necpálová et al., 2015). Consequently, proper management techniques, that can affect decomposition rates, fertilizer application, and improved crop yield potential may increase production, and maintain or even increase SOC in the future.

3.6. Projected change in soil nitrate leaching under different climate scenarios, fertilizer and cultivar treatments

Table 1 showed that soil nitrate leaching beyond the root zone at 1.2 – 10 m at the end of the simulation was determined by all factors including N fertilizer rate, climate change scenarios, and RUE_B . Although increasing N fertilizer increased projected N leaching, the amounts were generally small under most of the scenarios in this study compared to that under C85, C45 and H45. The worst scenario was C85 with 559 kg N ha⁻¹ projected leaching when 150 kg N ha⁻¹ was applied every year and using a current cultivar with 38 mg C kJ⁻¹ RUE_B , followed by C45 and H85. The increase in precipitation under C85 caused more water to move to deeper depths resulting in increased N mineralization and more nitrate leaching. However, if a higher yield potential cultivar was used the projected leaching was significantly reduced. The relatively high leaching under C45 and H85 was associated with both high precipitation and low projected yield and biomass, while

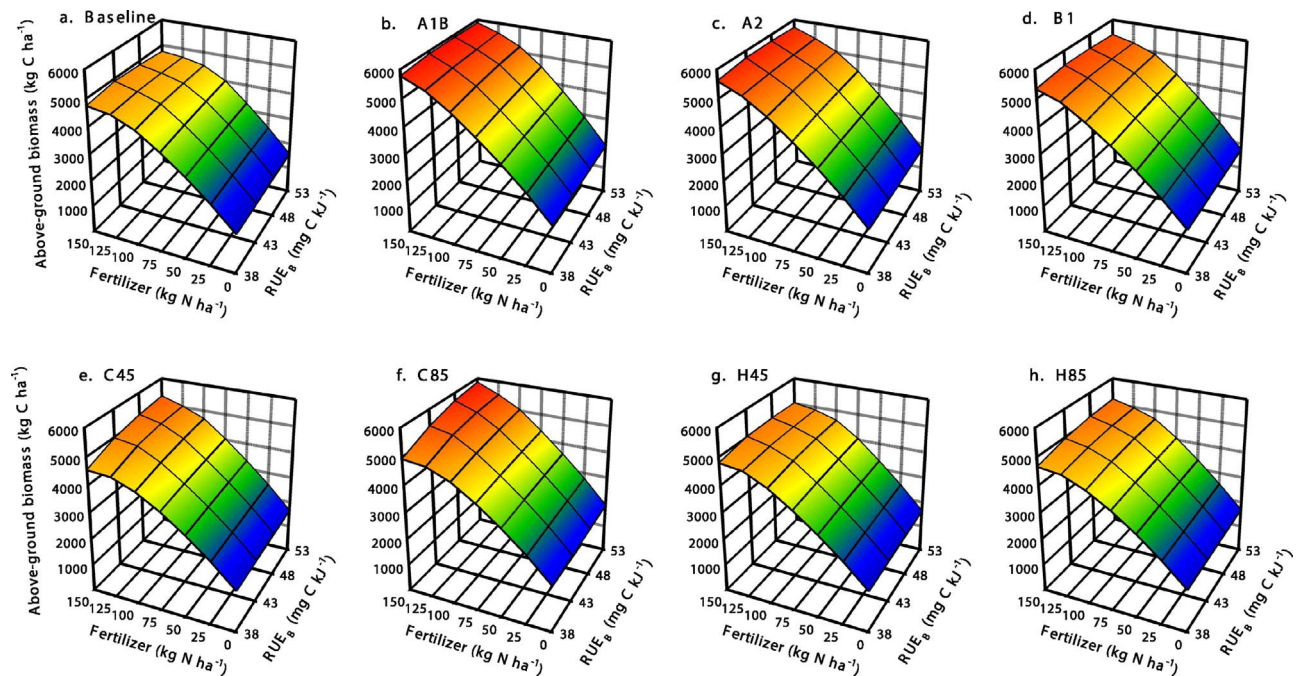


Fig. 4. Projected mean above-ground biomass over 60 years (2017–2076) under different climate scenarios, N fertilizer rates and RUE_B.

increasing yield potential could reduce leaching under these scenarios.

By improving RUE_B to 43, 48 and 53 mg C kJ⁻¹, nitrate leaching was reduced at the end of the simulation in 2076 by 71, 90 and 95% with N rate of 150 kg N ha⁻¹, respectively. Under scenarios of C85, C45 and H85, and with 150 kg N ha⁻¹ fertilizer, the averaged reduction of leaching by improving RUE_B from 38 to 43, 48, and 53 mg C kJ⁻¹ at the end of the simulation in 2076 was 71, 90 and 95%, respectively. This indicates that increasing yield potential can increase N uptake so as to reduce leaching effectively (Sainju, 2007). Alternatively, by ensuring that available soil nitrogen is maintained (decrease the leaching) the biomass production may increase (Lee et al., 2012).

It is of interest to note that the projected leaching under the no N fertilizer treatment was often slightly higher than that under fertilized treatments (Table 1). Overall average leaching was 60, 42 and 61 kg N ha⁻¹ under rates of 0, 25 and 50 kg N ha⁻¹, respectively. This phenomenon was observed by Campbell et al. (2010) who attributed greater N leaching due to poorer crop growth associated with less than optimum N for crop growth. Our modeling results supported this hypothesis. The mean simulated annual soil N mineralization was about 25 kg N ha⁻¹, which was higher than the total N loss (about 20 kg N ha⁻¹) including harvested grain N and projected total N emission (N₂O, NO and N₂) under the no fertilizer treatment. Therefore, in a

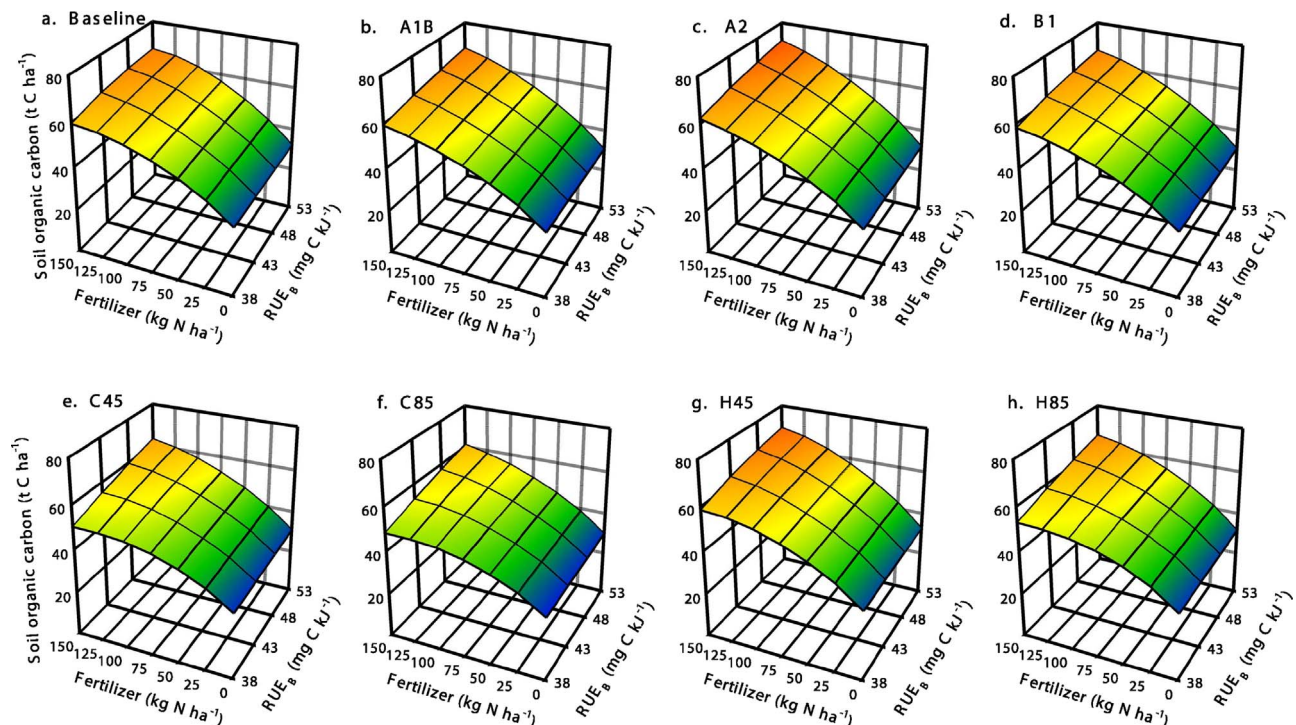


Fig. 5. Projected soil organic carbon at the end of the simulation in 2076 under different climate scenarios, N fertilizer rates and RUE_B.

Table 1

Effects of climate change scenario, N fertilizer rate (kg N ha^{-1}) and radiation use efficiency of biomass (RUE_B , mg C kJ^{-1}) on soil N leaching (mean and $\pm$ of the 95% confidence interval, CI, kg N ha^{-1}).

N rate	RUE_B							
	38		43		48		53	
	Mean	$\pm$ CI	Mean	$\pm$ CI	Mean	$\pm$ CI	Mean	$\pm$ CI
Baseline								
0	8.4	0.7	7.2	0.6	6.2	0.6	5.5	0.6
25	2.2	0.3	2.0	0.3	1.8	0.2	1.7	0.2
50	2.8	0.4	2.4	0.3	2.1	0.3	1.9	0.3
75	3.4	0.4	2.8	0.4	2.4	0.3	2.1	0.3
100	3.9	0.4	3.1	0.4	2.6	0.3	2.3	0.3
125	4.1	0.5	3.4	0.4	2.8	0.4	2.5	0.3
150	18.2	7.2	4.9	2.3	3.7	0.9	2.5	0.6
A1B								
0	14.1	1.2	11.7	1.2	9.6	1.1	8.0	1.1
25	4.6	0.6	3.7	0.5	3.1	0.5	2.7	0.5
50	6.2	0.7	5.0	0.6	4.2	0.6	3.6	0.6
75	7.8	0.9	6.1	0.8	5.2	0.7	4.5	0.6
100	8.8	1.0	6.8	0.9	5.7	0.8	4.9	0.8
125	9.6	1.3	7.2	1.1	6.0	0.9	5.3	0.9
150	11.9	2.7	7.8	1.3	6.2	1.1	5.4	1.0
A2								
0	15.1	1.2	12.6	1.3	10.6	1.3	8.9	1.2
25	5.6	0.4	4.7	0.4	4.0	0.4	3.5	0.4
50	7.6	0.6	6.4	0.6	5.5	0.5	4.8	0.5
75	9.7	0.9	7.9	0.8	6.8	0.7	6.1	0.7
100	11.5	1.3	9.0	1.0	7.6	0.9	6.7	0.9
125	13.3	1.9	9.9	1.4	8.3	1.2	7.3	1.1
150	22.7	4.7	11.9	2.1	9.1	1.6	7.7	1.4
B1								
0	13.3	0.8	11.4	0.8	9.9	0.7	8.7	0.7
25	3.8	0.4	3.3	0.3	2.9	0.3	2.7	0.3
50	4.7	0.5	3.9	0.4	3.3	0.4	3.0	0.3
75	6.1	0.7	4.7	0.6	4.0	0.5	3.5	0.4
100	7.1	0.9	5.4	0.7	4.4	0.6	3.8	0.5
125	7.8	1.2	5.9	0.8	4.8	0.7	4.1	0.6
150	16.1	6.6	6.6	1.2	5.1	1.0	4.2	0.8
C45								
0	21.1	0.9	18.8	0.9	17.0	0.9	15.5	0.9
25	8.9	1.2	7.7	1.1	6.8	1.0	6.1	0.9
50	12.0	1.6	9.5	1.3	7.9	1.1	6.8	1.0
75	16.4	2.1	11.3	1.4	8.7	1.1	7.2	1.0
100	24.6	3.8	14.9	2.8	9.8	1.4	7.4	1.0
125	95.6	26.0	23.7	6.9	11.8	2.1	9.1	2.0
150	516.7	77.1	141.0	35.6	37.6	15.6	13.0	5.8
C85								
0	27.0	1.1	24.1	1.2	21.6	1.2	19.4	1.2
25	15.4	1.2	13.1	1.1	11.5	1.0	10.2	0.9
50	21.8	1.8	17.5	1.5	14.6	1.3	12.7	1.1
75	30.3	2.5	22.1	1.8	17.5	1.4	14.6	1.1
100	57.2	9.6	27.8	2.5	19.6	1.6	15.7	1.2
125	135.6	24.7	46.5	10.1	26.7	3.5	17.0	1.7
150	559.4	88.2	125.7	31.4	35.6	5.8	24.4	4.5
H45								
0	16.7	0.9	14.7	0.9	13.2	0.8	11.8	0.8
25	4.9	0.6	4.3	0.5	4.0	0.5	3.7	0.5
50	6.9	0.9	5.8	0.8	5.0	0.7	4.5	0.7
75	10.2	1.3	7.9	1.1	6.5	1.0	5.6	0.9
100	14.7	2.5	9.4	1.5	7.4	1.1	6.2	1.0
125	30.0	6.0	13.7	2.5	8.6	1.7	6.7	1.3
150	119.6	35.3	26.3	5.9	16.0	4.8	8.7	2.8
H85								
0	23.7	1.4	21.8	1.4	20.1	1.4	18.7	1.4
25	9.9	1.6	9.0	1.5	8.3	1.4	7.8	1.3
50	15.1	2.5	12.6	2.1	11.1	1.9	10.0	1.7
75	28.8	5.8	18.7	2.8	14.6	2.1	12.5	2.0
100	58.4	14.6	34.0	8.9	20.5	3.8	15.1	2.2
125	131.0	34.9	58.9	15.0	29.8	7.1	21.9	5.5
150	372.0	75.3	136.8	43.4	63.2	19.8	30.2	6.7

malnourished low biomass growing crop a portion of the accumulated nitrite will be gradually leached beyond the root zone. While, when fertilizer is added, the crop will develop normal or near-normal roots and uptake nitrogen including fertilizer N and mineralized N from the soil, so to reduce N leaching compared to no the fertilizer treatment.

3.7. Projected change in nitrous oxide emission under different climate scenarios, fertilizer and cultivar treatments

According to the simulation, the N application rate had the most effect on N_2O emission, followed by climate change and RUE_B (Fig. 6). For each increase of 25 kg N ha^{-1} fertilizer, projected mean annual N_2O emissions were increased by 34, 26, 22, 21, 26 and 39% for rates of 25, 50, 75, 100, 125 and 150 kg N ha^{-1} fertilizer, respectively. If there is no change of the management in terms of N rate (50 kg N ha^{-1}) and yield potential ($38 \text{ mg C kJ}^{-1} \text{ RUE}_B$), the projected N_2O emission will be increased by 43, 48, 26, 38, 71, 29 and 48% under climate scenarios of A1B, A2, B1, C45, C85, H45 and H85, respectively, compared to the baseline. The increase of projected N_2O emission is associated with the increase of projected precipitation. This estimation is lower than the projection by Tian et al. (2012) who projected an increase by 157–227% under climate change compared to emissions between 2000 and 2010 in North America; assuming no change in the management. By improving RUE_B from 38 to 43, 48, and 53 mg C kJ^{-1} , projected N_2O emission was reduced by 6, 10 and 11% with N rate of 100 kg N ha^{-1} , respectively, averaged over all climate scenarios. Because most soil N_2O emission occurs before seeding and the emission is associated with precipitation and soil moisture (Scheer et al., 2014), changing RUE_B has a small effect on N_2O emissions. Reducing the N fertilizer amount and improving the application method, such as split application, are effective measures to reduce N_2O emission under future climate (Dusenbury et al., 2008).

3.8. Selecting fertilizer rates to balance production and environment

Based on the simulation results, we can assess impacts of fertilizer rates on projected grain yield and environmental impacts (SOC, N leaching and N_2O emission) in the near future (2017–2046) and distant future (2047–2076). Assuming the cultivar grown in the near future has $43 \text{ mg C kJ}^{-1} \text{ RUE}_B$, the averaged projected yield over all climate change scenarios in this study will increase 18 and 35% if the fertilizer rate is increased to 75 and 100 kg N ha^{-1} , respectively, compared to the current rate (50 kg N ha^{-1} , Fig. 7a). If N fertilizer is further increased, the increase in projected yield will be small. Compared to the simulated yield ($1114 \text{ kg C ha}^{-1}$) under the baseline climate with fertilizer of 50 kg N ha^{-1} , the mean projected yield was increased by 11, 31, 50, 57 and 57%, respectively, with fertilizer rates of 50, 75, 100, 125 and 150 kg N ha^{-1} , which were lower than the needed increase rate (70%) by the world by 2050 (FAO, 2009). Other measures to increase production should also be taken. Similar to simulated yield the projected increase in SOC in the end of this period (2046) was also relatively high if the fertilizer is increased to 100 kg N ha^{-1} (Fig. 7b). The projected accumulated N leaching in 2046 increased with the increase of fertilizer rate, while the quantity was not very high (Fig. 7c). The projected N gas emission increased with the increased N fertilizer, while a sharp increases occurred when fertilizer was increased to 125 (58%) and 150 kg N ha^{-1} (122%) (Fig. 7d). Based on above-mentioned assumptions, it seems that in the near future (2017–2046) the appropriate N rate is 100 kg N ha^{-1} in order to increase production and reduce the environmental impacts.

Assuming the cultivar grown in the distant future (2047–2076) has $53 \text{ mg C kJ}^{-1} \text{ RUE}_B$, the projected yield increased concurrently with the increase of fertilizer rate without plateauing compared to the near future period when the rate increased to 150 kg N ha^{-1} (Fig. 7e). Compared to the simulated yield ($1114 \text{ kg C ha}^{-1}$) under the baseline climate with the fertilizer of 50 kg N ha^{-1} , the mean projected yield was

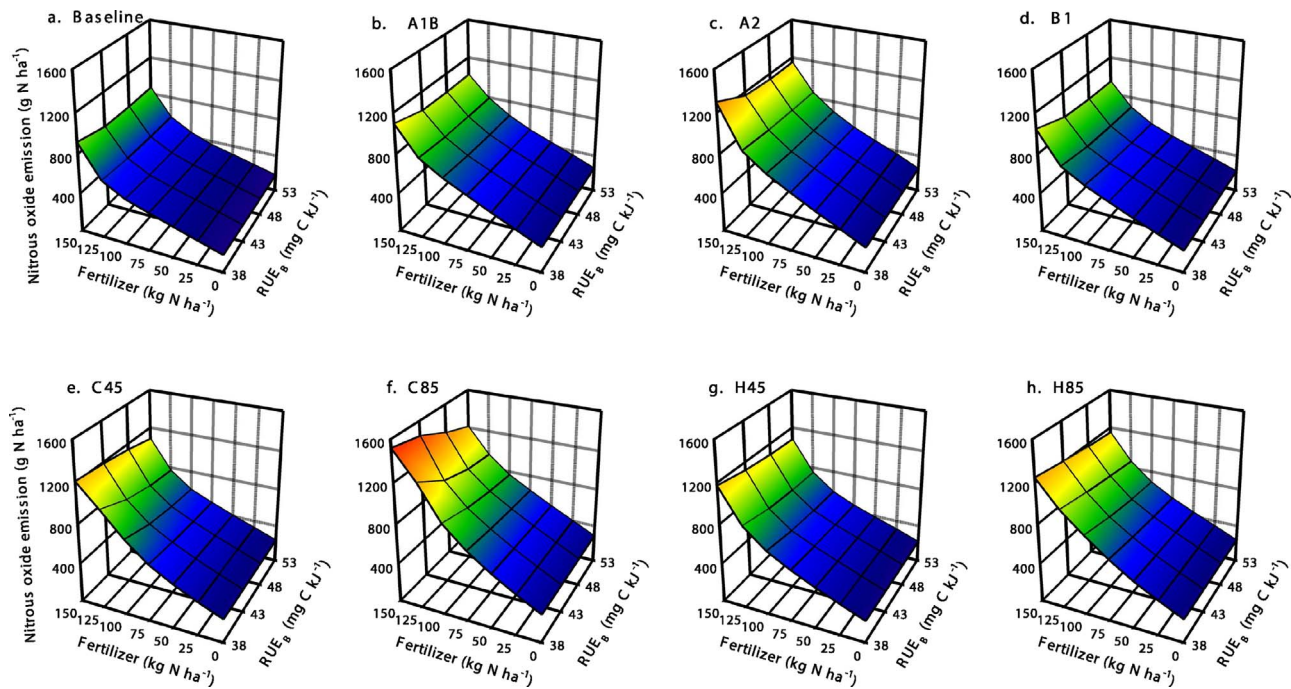


Fig. 6. Projected mean annual nitrate oxide emission over 60 years (2017–2076) under different climate scenarios, N fertilizer rates and RUE_8 .

increased by 21, 52, 81, 105 and 122% with the fertilizer rates of 50, 75, 100, 125 and 150 kg N ha^{-1} , respectively. The mean simulated N use efficiencies were 27, 23, 20, 18 and 16 kg C kg N^{-1} for rates of 50, 75, 100, 125 and 150 kg N ha^{-1} , respectively, which are higher than that under the near future period (the corresponding values were 25, 20, 17, 14 and 12 kg C kg N^{-1}). The projected increase in SOC in 2076 was similar to the increase in yield (Fig. 7f). The increase of N fertilizer resulted in more projected N leaching in the end of the simulation with high dispersions the means as expressed by standard deviation (Fig. 7g). It is caused by that different climate scenarios responded to N fertilizer rate differently as previously shown. Similar to the near future period, the projected N_2O emission increased dramatically (138%) when N was increased to 150 kg N ha^{-1} (Fig. 7h). In the distant future period (2017–2046), N fertilizer rate probably can be increased to 125 kg N ha^{-1} to further increase yield without too much environmental consequences.

4. Conclusions

Climate change has attracted unprecedented worldwide research attention in recent years. Adaptation strategies are especially important when facing food security under the frame of climate change. Ecological modelling has been approved for generating mitigation and adaptation strategies for optimum food production worldwide. To our knowledge, this work is the first attempt to use DAYCENT to project the impacts of climate change and N fertilizer rates with different wheat yield potentials on yield and environmental consequences including SOC, nitrate leaching, and N_2O emissions in a high latitude environment. The results of our study indicated that DAYCENT model worked well with the data sets after modification and calibration. An optimized strategy for yield increase and environmental impact abatement was to increase the yield potential and cautiously increase the nitrogen application rate. Therefore, the importance of breeding new cultivars with higher yield potential should be emphasized when making adaptation strategies to mitigate the impact of climate change. Increasing yield potential is an effective way to promote wheat production and protect

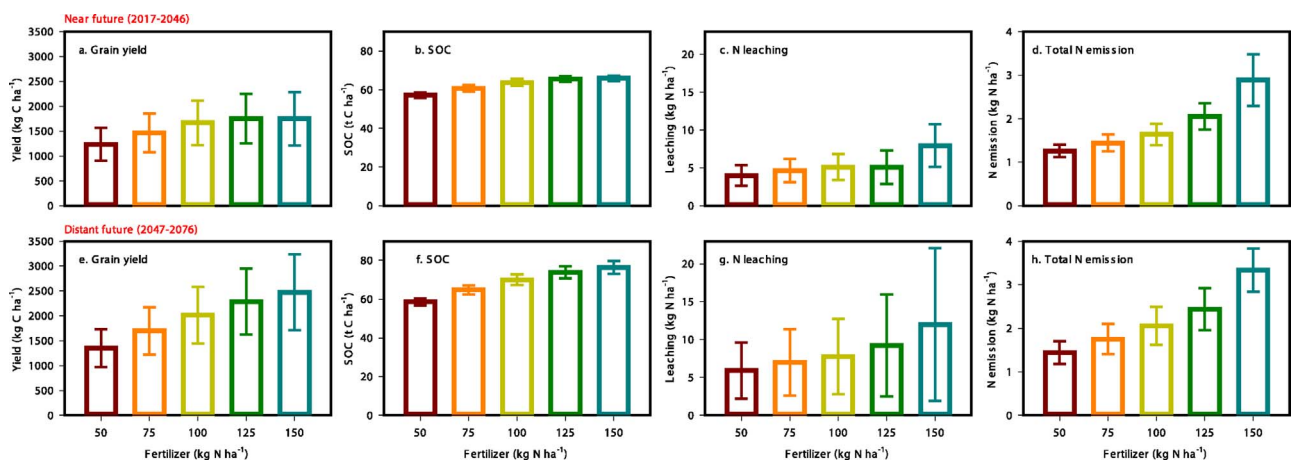


Fig. 7. DAYCENT-projected impacts of fertilizer rates on grain yield and environmental impacts (final SOC, accumulated N leaching and mean total N emission) by growing wheat cultivars of 43 mg C kJ^{-1} RUEB in the near future (2017–2046), and growing wheat cultivars of 53 mg C kJ^{-1} RUEB in the distant future (2047–2076).

the environment (increase soil organic carbon content, decrease N leaching and N₂O emissions). However, caution should be exercised, because the uncertainty is large in greenhouse gas emission and climate change scenarios as well as the modelling approaches. Further study should include other climate change models and ecosystem models in order to quantify the simulation uncertainty.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.eja.2017.12.005>.

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